national accelerator laboratory

TM-159
0480

OUTLINE OF MAIN-RING CONTROLS

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I Enumeration and Interconnection of Control Centers

This note is not intended to be final but only to indicate current thinking to form the basis for further discussion.

In order to reduce the number of parameters we make the following assumptions:

1. Information is collected and transmitted from local control stations. There are 28 local control stations (LCS) designated as follows:

LCS 1-24	Main-Ring Equipment Houses
LCS-RF	RF Building
LCS-B	Booster Control in Cross-Gallery Control Room
LCS-E	Extraction System in Transfer Gallery
LCS-A	Abort (house in Abort Straight Section)

In this numbering scheme LCS-1 and LCS-2 are in the equipment houses nearest the cross gallery and because of shorter transmission distance than to LCS 3-24 will have a special status as will be detailed below.

2. Each LCS can be operated independently.

3. Each LCS has a control computer, labelled LCC. For LCC 1-24 and LCC-A a 4096 12-bit word computer is assumed.

4. In the Cross-Gallery Control Room, called henceforth Main-Ring Control Station (MRCS), there is a 16-18 -bit Main-Ring Control Computer (MRCC).

5. The Main-Ring Control Computer (MRCC) does <u>not</u> control the whole accelerator. The links to LCC-RF, -B, and

-E serve to exchange status information. The hierarchy of computers can thus be represented as in Fig. i. The eventual evolution of a single control computer could occur either from MRCC or LCC-E.

6. It is not planned to have the LCC's talk to each other. Clearly this capability, if needed, could be added to the system described.

II List of Hardware Systems

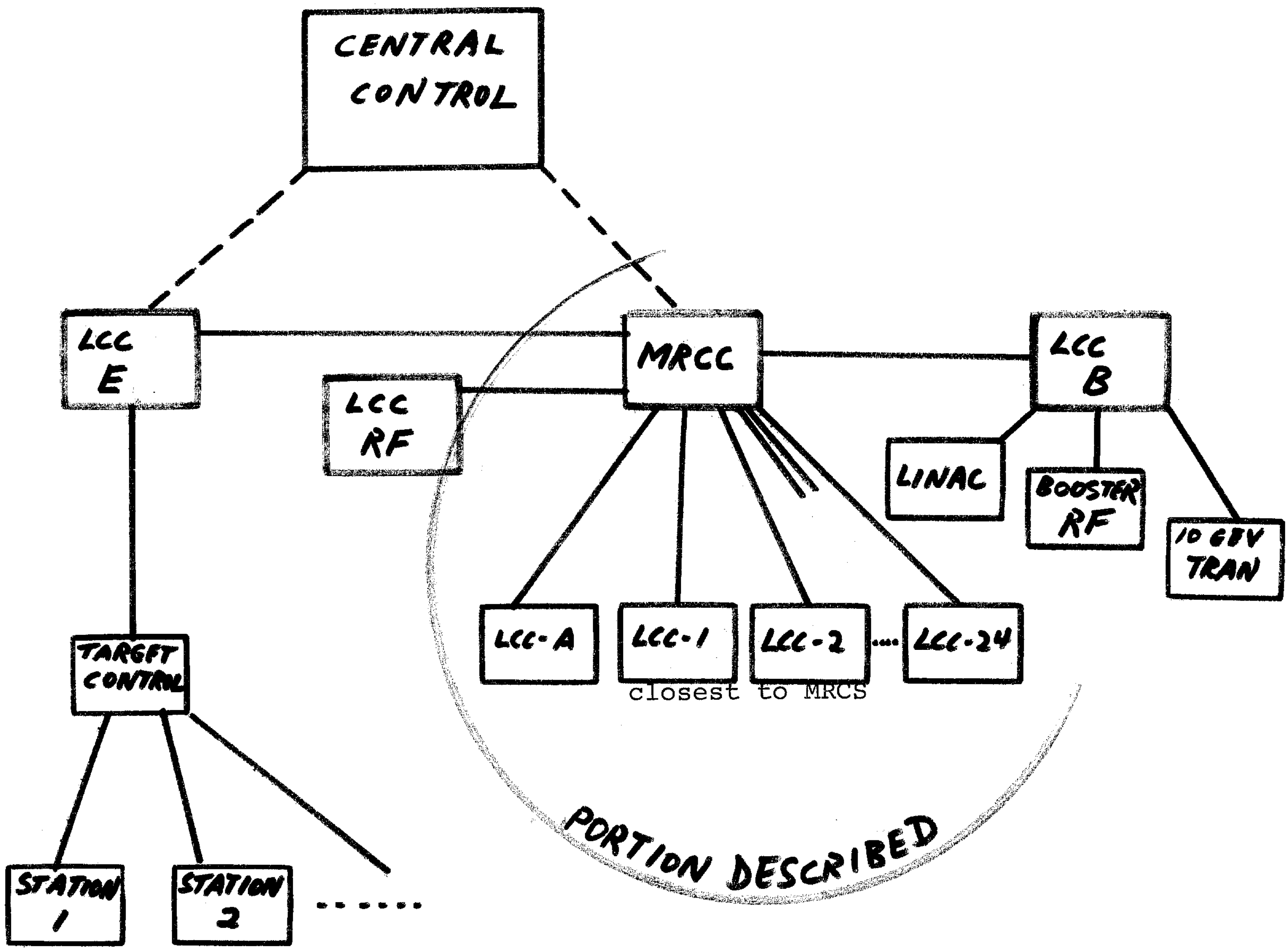
Multiplex

One form of interconnection between the MRCS and the LCS's will be via digital transmission time multiplex, which can operate in both random address and sequential address modes depending on the system it is servicing.

The following hardware systems will be serviced by the multiplex system. In this context "serviced" means monitor and/or control.

1. Main Magnet Power Supplies
    - 1.1 Quadrupoles
    - 1.2 Bending
2. Auxiliary Magnet Power Supplies
    - 2.1 Dipoles
    - 2.2 Trim Quadrupoles
    - 2.3 Special Trim Quadrupoles
    - 2.4 Sextupoles
    - 2.5 Special Sextupoles
    - 2.6 Skew Quadrupoles

FIGURE 1


CENTRAL CONTROL
LCC E
LCC RF
MRCC
LCC B
LINAC
BOOSTER RF
10 GEV TRAN
LCC-A
LCC-1
LCC-2
LCC-24
closest to MRCS
TARGET CONTROL
STATION 1
STATION 2
PORTION DESCRIBED

2.7 Miscellaneous Bump Magnets (extraction)

3. Vacuum System

   3.1 Ring Pump Power Supplies

   3.2 Gate Valves

4. Abort System

   4.1 Magnets and their power supplies

   4.2 Radiation Monitors

5. Scraper System

   5.1 Magnets and their power supplies

   5.2 Radiation Monitors

6. Main Magnet Fault Detection

7. Wire Survey System

8. Beam Position Monitoring

   8.1 Wide Band

   8.2 Ionization Type

   8.3 Closed orbit

9. Radiation Monitoring

10. Magnet Water Cooling

11. Service Function Monitoring

   11.1 Tunnel fans

   11.2 Smoke alarms

   11.3 Fire alarms

   11.4 Sump pumps

   11.5 Humidity and Temperature

   11.6 Circuit breakers (in substations)

   11.7 Door and safety interlocks (monitoring of hard-wire system)

12. Interface to other computers
    12.1 Booster (this in turn converses with Linac, Booster RF, 10 GeV transfer)
    12.2 RF (Main-Ring)
    12.3 Extraction

Direct Wires

In addition to the above, direct (hard) wires are required by the following:

1. Critical trigger signals
    1.1 Booster↔Main-Ring
    1.2 Main-Ring↔Main-Ring RF
    1.3 Main-Ring↔Extraction
    1.4 Abort Trigger line around whole ring with prompt abort signals supplied by devices in LCC's as well as MRCC.
2. Personnel safety interlocks
3. Wide band beam monitor(s)
4. Master timing signal (Booster generated)
5. Communications
    511 Voice (e.g. 2-way radios on vehicles)
    5.2 Telephones
    5.3 Paging devices (portable)
    5.4 TV (in general quite limited)

III Description of Hardware Systems Connected to Multiplex

1. Main Magnet Power Supplies

   There is a total of 36 power supplies, 24 for the bending magnets and 12 for the quadrupoles. Let the latter be placed in even numbered LCS's. The bending magnet supplies in LCS-1, -2 and the quadrupole supply in LCS-2 have special status to provide the "fine" tuning to control the magnet current program to the required $1/10^4$ accuracy.

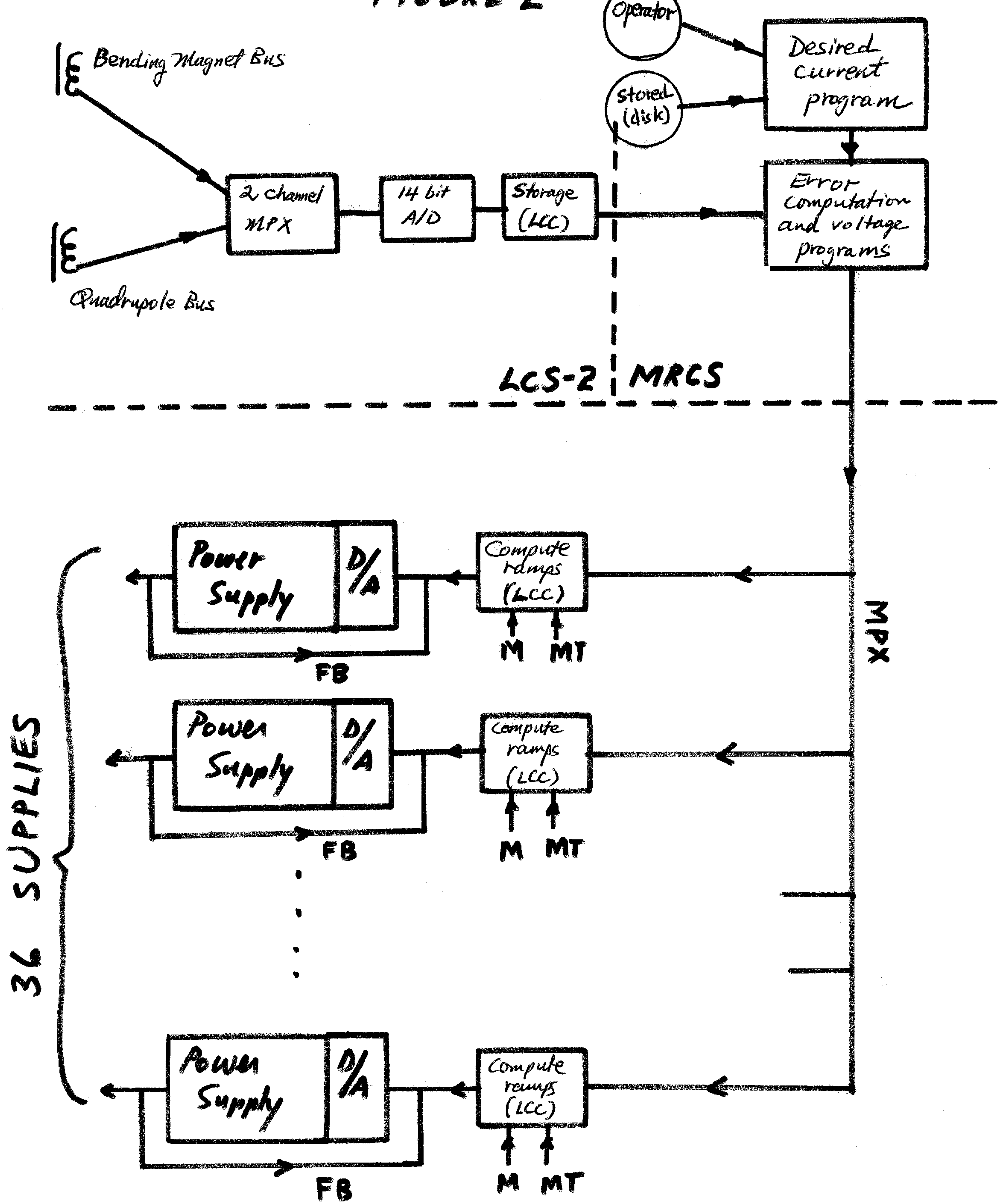
Figure 2 illustrates the arrangement. The actual magnet currents in the bending magnet bus and the quadrupole bus are sampled at a maximum rate of 1 kc, stored locally and sent by multiplex transmission between accelerator pulses to the MRCC. Here they are compared with the desired current pulse which is put into the MRCC either by the operator or from a storage device. The desired voltage programs for the 36 power supplies are computed and transmitted for the next pulse. (Current monitoring may be needed in more places around the ring than shown in Fig. 2)

In keeping with the philosophy of independent control, a voltage program can be put directly into the LCC, e.g. by paper tape, and the power supply in that LCS operated independently.

In the proposed scheme, the three "fine" control supplies differ from the coarse ones only in the amount of information transmitted and stored, i.e. in the fineness of the voltage program. A voltage program can be represented as a series of co-ordinate pairs V(t) and the LCC can generate the ramps connecting them.

Table I shows the amount of data anticipated. Since

FIGURE 2



MPX = Multiplex transmission
MT = Master Timing
M = Manual Input of Voltage Program to LCC
FB = Local Feedback on each Power Supply

only voltage and time changes within a pulse are necessary, 12-bit words are probably adequate.

Table I

Supply	Number	Data Storage - 14-bit words or equivalent (each supply)	Data Transmission 14-bit words or equivalent (each supply)	
			Initialization	Each pulse (only updates sent)
"fine"	3	480	480	100
"coarse"	33	10	10	2

Power Supply Monitoring

(a) The actual power supply voltage will be monitored and can be displayed locally. Up to 500 points on the voltage pulse can be digitized, stored locally, and transmitted to the MRCC. In the MRCS, the programs will enable the operator to display the desired, actual or difference voltage pulses for all 36 power supplies.

(b) Interlock Chain and Ground Fault Detectors (70 bits assumed for each interlock chain but it is only scanned if there is an interrupt.) These turn off the power supply and in addition do two things:

1. Send a prompt abort signal on the hardwire abort system.

2. Send an interrupt to the LCC which reads the interlock chain and other fault indicator data into core.

Then when the MRCS operator intervenes, he can ask for transmission of this data to the MRCC. A power supply fault may trigger a rapid sequence of other events. If the initial interrupt and sampling of interlock and fault status is rapid enough then the history of the problem can be recreated.

(c) Ground currents are monitored and this information used to correct voltage programs.

2. Auxiliary Magnet Power Supplies

(ref. F. Shoemaker, Main Ring Correcting Magnets, TM-147, Jan. 16, 1969)

2.1 Dipoles

There are 200 individually controlled DC power supplies. Since a setting accurate to 1% is adequate, a 7-bit + sign or 8-bit computer word can be used to set each dipole level. If an off-on bit is added, 9-bits for each magnet transmitted from the MRCS will set the correction levels. If this level is stored locally then only update information need be sent on each accelerator pulse.

For monitoring purposes it should be sufficient to have 2 bits, one that indicates the power supply is on and delivering current, one that says the power supply is regulating.

Figure 3 illustrates the control and monitoring arrangement.

2.2 Trim Quadrupoles

There are 200 trim quadrupoles in series which

FIGURE 3

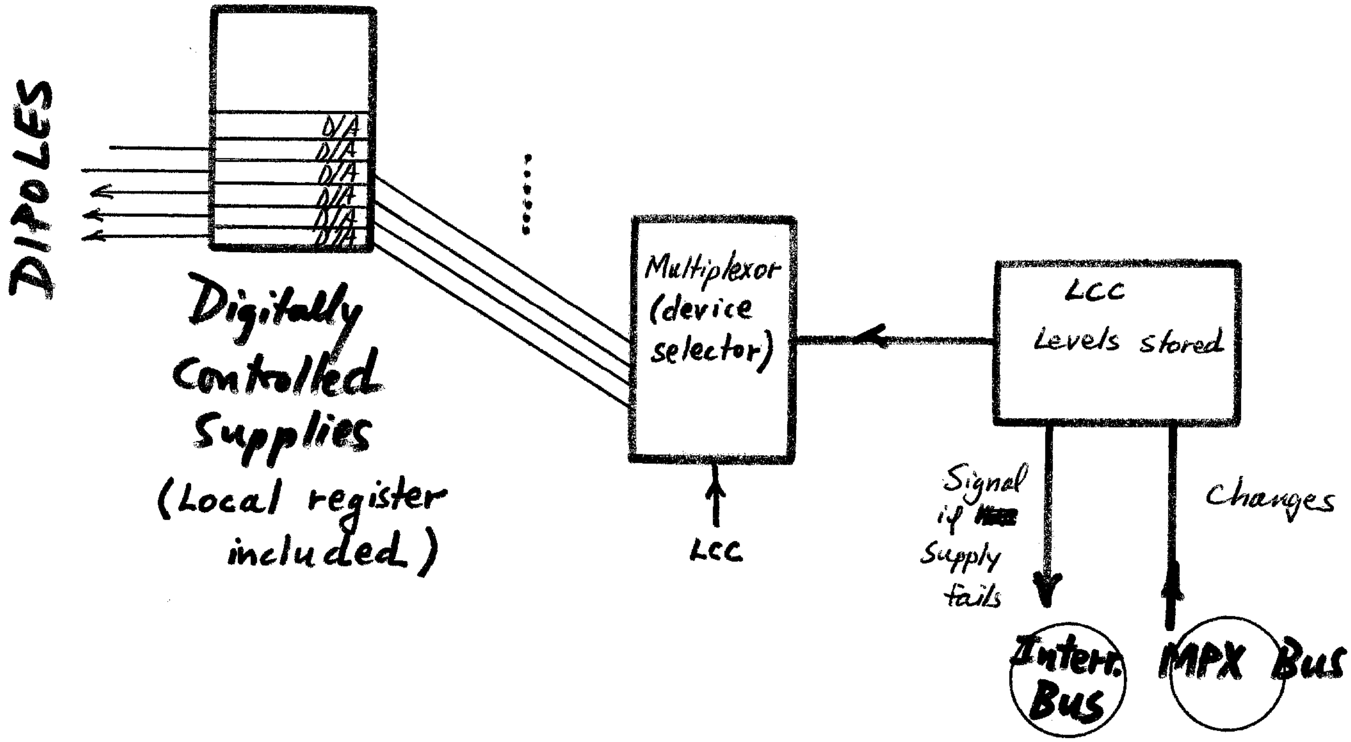
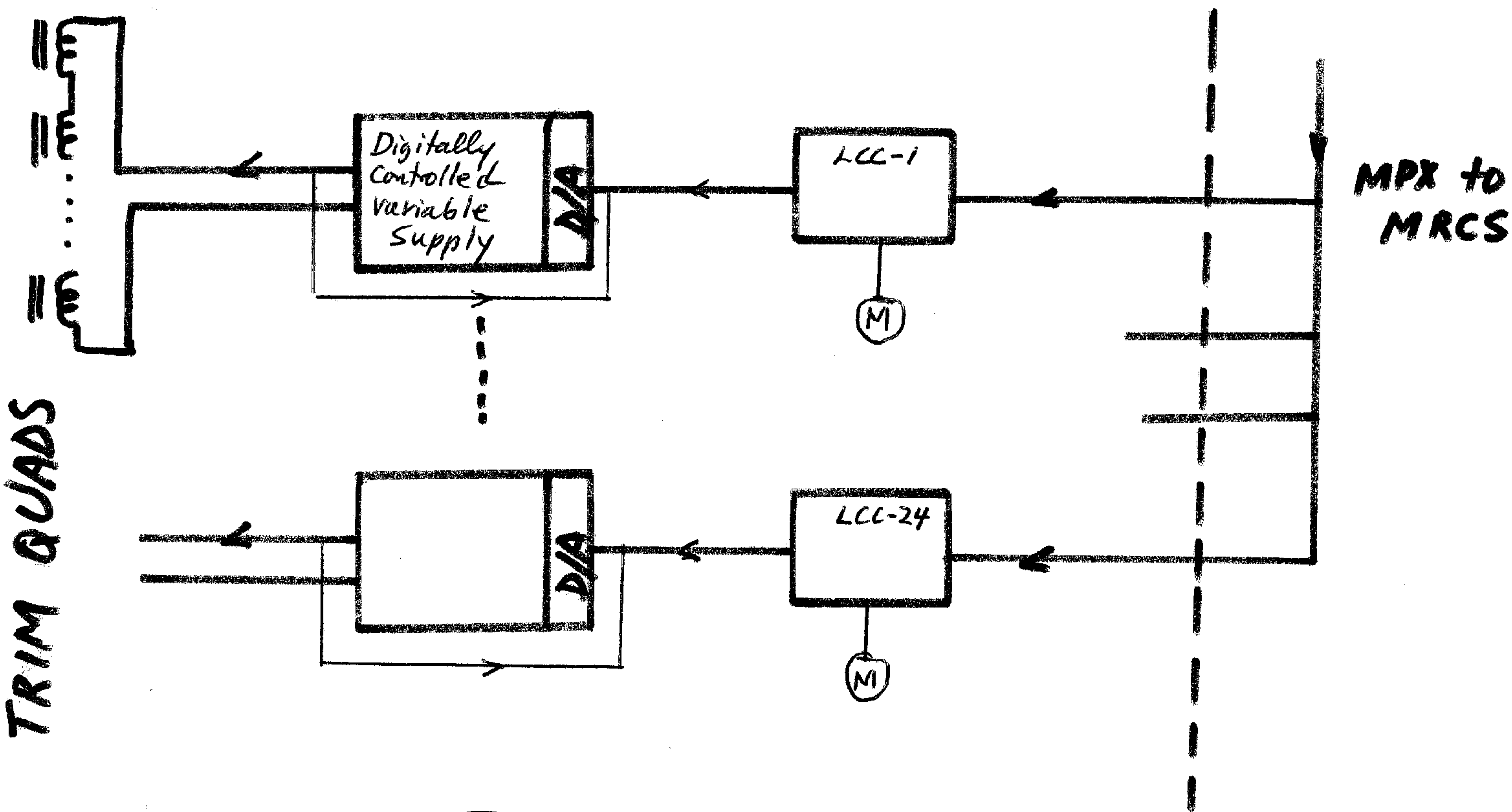


FIGURE 4



M = Manual Program Entry

can be powered by 24 200 watt power supplies. These must be programmable at several hundred cycles/sec.

In the stability pattern the trim quadrupoles move the operating point in a direction perpendicular to the motion caused by varying the main quadrupole current. The trim quads buck out ripple in the main quadrupole power supply and also smooth the spill. Like the main magnet supplies, only the 2 "electrically opposite", i.e. in LCS-1, 2 need have fine control.

Figure 4 shows the Trim Quadrupole control system. During initialization the voltage program for each power supply can be transmitted. During operation only updates need be sent. The difference in the "fine" and coarse" control is in the quantity of data needed as shown in Table II.

Table II

	bits/word	pairs of words to define voltage program		additional spill control words	Transmission no. of words	
		during injection, acceleration	spill		Initialization	Updates
Trim Quad Supplies in LCS-1,2	12	10	10	300	340	≈304
Trim Quad Supplies in LCS-3,24	12	10	10	-	40	4

In addition to a set of V(t) "coordinates" defining a voltage program where the connecting ramps are filled in by the LCC, the "fine" control has a block of 300 levels which control the supply at evenly spaced 3 msec. intervals during the spill. These numbers originate in a spill sensor and are supplied from LCC-E. The output levels are computed in a learning function generator and sent in <u>real time</u> to the trim quadrupoles. An update must be either a retransmission of the whole block of words or if only some words are sent, a relative address within the block for each word being modified must be sent.

Three kinds of feedback are present in the system:

(a) Local voltage (analog) feedback with a monitoring bit sent out indicating if the supply is within its regulating range.

(b) Hum bucking analog feedback to compensate for the main quadrupole ripple. The amount of bucking would be controlled digitally by the LCC.

(c) Software feedback in the MRCC using the spill as a sensor and a learning function program to smooth the spill out.

2.3 <u>Special Trim Quadrupoles</u>

There are 16 DC supplies providing sin 40 θ, cos 40 θ, sin 41 θ, cos 41 θ corrections, both horizontally and vertically at injection. The control and monitoring of these magnets is the same as for the dipoles. (2.1)

2.4 Sextupoles

There are 200 sextupoles in series powered by 24 500 watt DC supplies, one in each LCS, controlled digitally as for the dipoles. (2.1)

2.5 Special Sextupoles

There are 4 special sextupoles providing sin 61 θ and cos 61 θ corrections at injection. These magnets are powered by 100 watt digitally controlled DC supplies. The controls and monitors are the same as for the dipoles. (2.1)

2.6 Skew Quadrupoles

There are two skew quadrupoles systems:

(a) Six in series provide 0 θ correction. These are programmed like the trim quadrupole supplies. Since the magnets are evenly spaced around the ring, six separate power supplies are necessary, each controlled like the trim quadrupole supplies in LCS 3-24. (2.2)

(b) Eight magnets provide sin 40 θ, cos 40 θ, sin 41 θ, cos 41 θ correction at injection. These eight magnets are powered by DC supplies, controlled and monitored like the dipoles. (2.1)

2.7 Miscellaneous bump magnets used for extraction

To estimate the number of bits, four units each needing 1000 bits is assumed.

3. Vacuum System

3.1 Ring Pump Power Supplies

There will be 24 power supplies, one in each equipment house with separate HV leads, disconnect switch (relay), and current monitoring to each of the 822 ring vacuum pumps. This total assumes 786 15-20 ℓ/sec pumps and 36 50ℓ/sec pumps in the medium and long straight sections but does not include special pumps in the Abort, RF, Extraction, Injection straight sections. Control and monitoring is needed on each power supply as well as on each pump as shown in Fig. 5. $\gtrsim$1% readout on log I, where I α pressure, is adequate so 7 bits are allowed for the individual pump current monitor which is switched sequentially from pump to pump by a program initiated either from the MRCC of the LCC but carried out by the LCC.

As shown in Fig. 5 there is only one voltage regulated, current limited supply for ~35 pumps. Upon further study it may appear preferable to have separate starting and holding supplies. If the overcurrent relay on a pump trips it can mean either a large pressure rise in a portion of the ring building or a shorted HV connector. By having individual on-off control on each pump an operator can determine which of these two situations has occurred and in the case of a bad pump it can be left disconnected and flagged in the computer stored maintenance records for attention in the next shutdown.

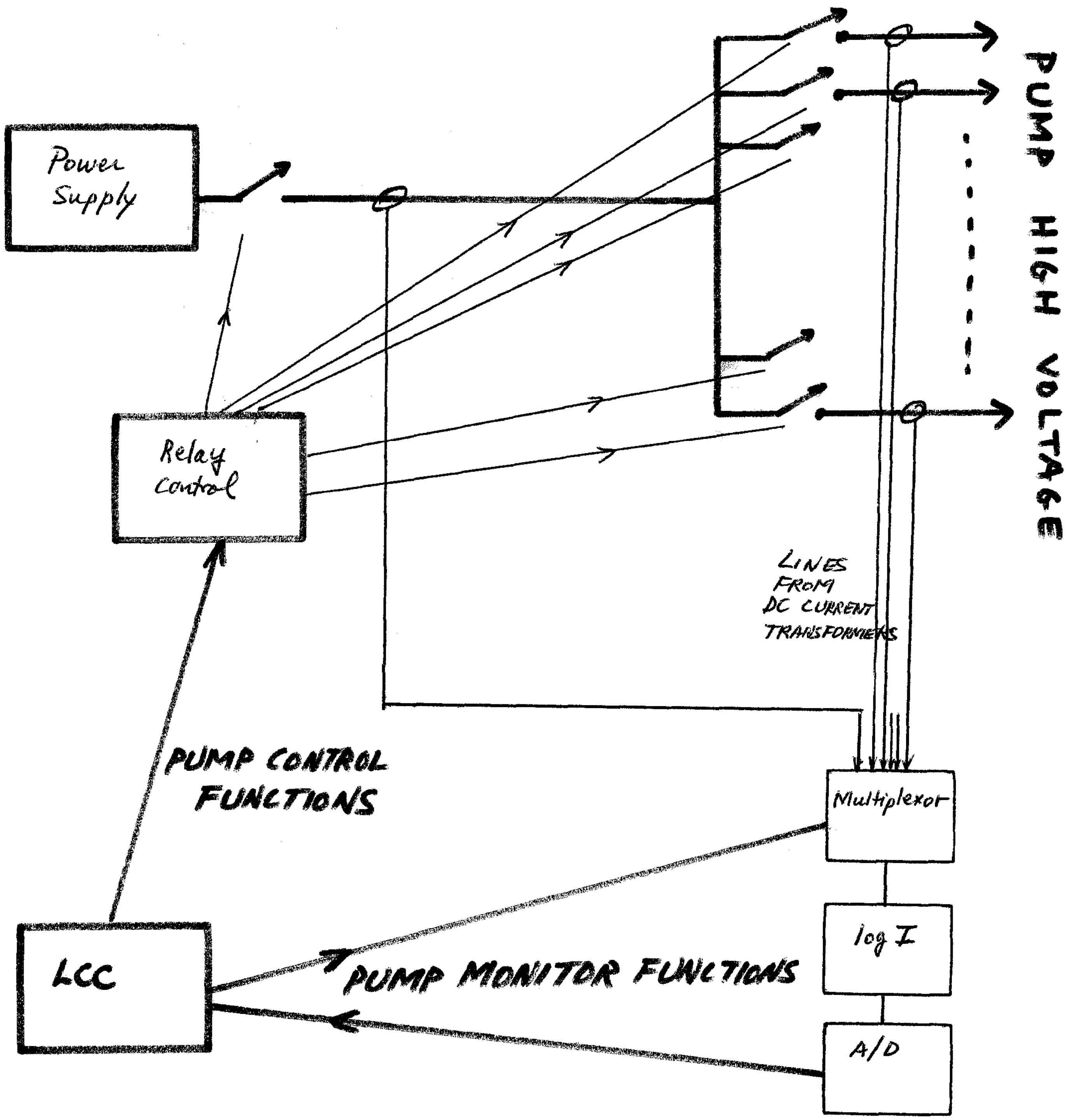
3.2 Gate Valves

There are 18-24 gate valves in the ring. The number of control and monitoring bits is small:

control: open, close
monitor: open, close
air pressure on, off

Complexity in the gate valve system will arise in the software if it seems desirable to use fast acting valves and attempt to prevent a pressure rise in one sector of the

FIGURE 5


Power Supply
Relay control
PUMP HIGH VOLTAGE
LINES FROM DC CURRENT TRANSFORMERS
PUMP CONTROL FUNCTIONS
Multiplexor
log I
A/D
LCC
PUMP MONITOR FUNCTIONS

ring from propagatimng around the ring. This will be discussed in the section on software.

4. Abort System

4.1 Magnets and their power supplies

Since the abort system is not yet designed only approximate statements can be made about data dtorage and transmission needs. The beam bump that is generated by pulsed magnets at abort time must match the momentum program of the accelerator. This can be done by local analog or digital control.

A prompt abott trigger will be sent on a hard-wire abott line going around the rimng and could be caused in several different ways:

(1) Main magnet power supply failure (see Section 1)

(2) Main magnet fault detected (see Section 6)

(3) By the operator in the MRCS setting a knob to abort at a given momentum on every acceleratorppulse.

(4) By a signal returned either before or during flattop from LCC-E that the Extraction system can't operate on that particular pulse.

(5) Excessive radiation in some area.

4.2 Radiation Monitors

There will be radiation monitoring of the abort operation. To estimate information requirements, 10 monitors similar to those described in Section 9 are assumed.

5. Scraper System

5.1 Magnets and their Power Supplies

There are four programmed magnet triplets to produce orbit bumps: two horizontal triplets (25kw) and two vertical triplets (11kw). For information storage assume 50 words to each of them from the nearest LCC can be used to define their voltage program so they will track the momentum of the beam. Standard interlock and output pulse monitoring will be assumed.

5.2 Radiation Monitors

There will be radiation monitors, say 5/scraper or 20 total for bit counting purposes, specifically connected with the scraper operation, but with control and monitoring aspects similar to the ring radiation monitors described in Section 9.

6. Main Magnet Fault System

Each pair of bending magnets (387 signals) and the top and bottom coils of each quadrupole (240 signals) will be connected in Wheatstone bridges, driven by the magnet voltages. The unbalance current, after transformer coupling to bring it to ground level will be monitored. These unbalance currents can be digitized with 7-bit + sign accuracy, stored in the LCC and transmitted as a block of data to the MRCC upon request. If any of the $\sim$26 unbalance currents in each utility house exceeds a preset level a trigger for prompt abort will be generated.

7. Wire Survey System

The total number of analog monitoring points is the following:

(1) Each quadrupole will have four signals, a horizontal and vertical unbalance current at each end of the magnet for a total of 960 signals.

(2) The 240 wires each have an AC current flowing in them which can be measured.

(3) Vertical lines passing through a similar "H-magnet" pickup as the horizontal wires can be used to give information on magnet tilt. If two of the 5 piers in each 1/2-cell are thus equipped, this makes 384 current and 384 pickups to monitor.

The total of ∿2000 signals or ∿85 per equipment house need be monitored only infrequently. There is no need to store the information in the LCC, although it can be used as a buffer register for connection to the multiplex transmission bus.

In order to interpret the vertical quadrupole measurements the wire sag must be calculated. This can be done if the tension is measured. A tension measurement can be performed by putting DC on the wire and a variable frequency AC excitation of a few cps on the pickup and measuring the resulting amplitude as a function of frequency.

All the survey functions in each house can be handled by one (1) each DC power supply, variable frequency AC power supply, A/D converter with switchabłe gain, and a set of stepping relays or gates. A single computer word can supply address and control bits; a single word back is the measurement desired.

8. Beam position monitoring

(fef. F.C. Shoemaker, "Main Ring Beam Sensing", Jan. 23, 1969, TM-150)

The concepts here are still evolving but at least three systems habe been discussed. They each represent a heavy demand on the control system.

8.1 Wide band beam positioon monitor at a single position along the ring. If this position is close to the MRCS direct coax lines can be used. Pickup signals can be combined invvarious ways to give the total beam current, the x and y positions, and the quadrupole moment and skew quadrupole moment of the beam shape. All this can be displayed as a function of time. With 300 mcs coax the individual bunches are clearly seen.

8.2 Ionization

(ref. C.D. Johnson and L. Thorndahl, "The CPS Gas-Ionization Beam Scanner", paper presented at the 1969 National Accelerator Conference.)

Even more detailed information on the shape of the beam as a function of time can be obtained from a scan (using coossed electric and magnetic fields) of the electrons released by ionization of the resddual gas by the beam.

Discussion of 8.1 and 8.2

8.1 gives the best time resolution, and 8.2 the best spatial resolution information available. Both these systems are suited to oscilloscope display. Since several different time bases may be of interest, and since the beam repetition rate is low, several memory type 'scopes are indicated for each of these monitors. Wide band coax bringing the signals into the control room then are hooked to the 'scopes. Each 'scope has a potential information content of $\sim 500^2$ or $1/4 \times 10^6$ bits. If 10 'scopes are used (e.g. x, y, quad, skew quad, x and y from the ionization monitor, and several sweep speeds or delayed trigger) this means 2.5×10^6 bits. As described, these systems then do not belong in this section: systems serviced by the multiplex system.

Let's consider this number for a moment. First, it seems like a generous amount of information for a few machine operators to digest every four seconds. Even so it is only a small fraction of the total information content arriving on the coax lines. Mush of such displays are base lines, in other words, perhaps only 5% of the 'scope faces contain non-redundant information. In scanning the 'scope face bits need only be sent when "white" starts and when "white" ends (like many spark chamber film scanners). This means that if $1/20 \times 2.5 \times 10^6$ or 125,000 bits are transmitted every four seconds the 'scope displays can be reconstituted in the MRCS. This is not an unreasonable load on the mulitplex system and if this philosophy is adopted it removes the restrictions that systems (1) and (2) are limited to one each and must be in the LCS's nearest the MRCS. But these restrictions may be unimportant in the application of these beam sensors.

The 10^5 bits is still high for storage in the LCC. A way around this problem is local memory scopes with gain controls, sweep speed and delayed trigger operated remotely via the multiplex bus. For close locations a photograph can be taken, developed in a few seconds by forced processing and sent by pneumatic tubes to the MRCS for projection. (This is done in the war room of the SAGE defense system.)

Another solution is closed circuit TV. A single camera can be used mounted on a turret to look at several scopes. The sweep can be controlled by the LCC. Each sweep line can be loaded into a 500-bit buffer from which the computer squeezes the non-redundant information referred to above. The computer stores up one scope picture - $\sim$1000 12-bit words - and transmits it.

The above discussion ignores the information contained in the z- of intensity axis. This can be useful and it may turn out upon detailed study that a straightforward closed circuit TV system is the best.

Going through the optical medium isn't necessary if circuitry (S-H, A/D) can keep up with the real time data rate. A scheme to investigate is storage devices such as disks or drums allowing fast recording (>1 mc word rate) and slow readout ($\sim$0.1kc word rate). If digitizing and recording fast won't work then direct reading of analog signals (video tape) can be used and digitizing from the analog tape done during slow readout.

8.3 Closed orbit measurement

In order to measure and display the closed orbit at a given time in the acceleration cycle 200 beam monitors, 100 vertical and 100 horizontal, are placed in the mini-straight sections. Each of the 200 monitors delivers two signals: sum and difference:

This information is needed for computation of magnet realignment, and can be used for setting the correcting dipoles. It is also needed for injection and extraction kicker magnet adjustments.

The beam position indicators around the ring can be operated by averaging their signal for 80 μsec. A map of the closed orbit distortions is produced. The information demands of this system are:

(1) Control: 6 12-bit numbers sent and stored in each LCC telling at what time to measure the orbit. The time constant should also be switchable.

(2) Monitor: 6 x 400 = 2400 signals or 100 per LCS. Each of these can be 8 bits and stored in the LCC for sequential transmission between pulses.

Figure 6 shows the systems.

Two subsets (similar to the above) that may be needed are:

(1) A fast S/H circuit to look at an individual bunch as it goes around. This would come before the integrated in

FIGURE 6

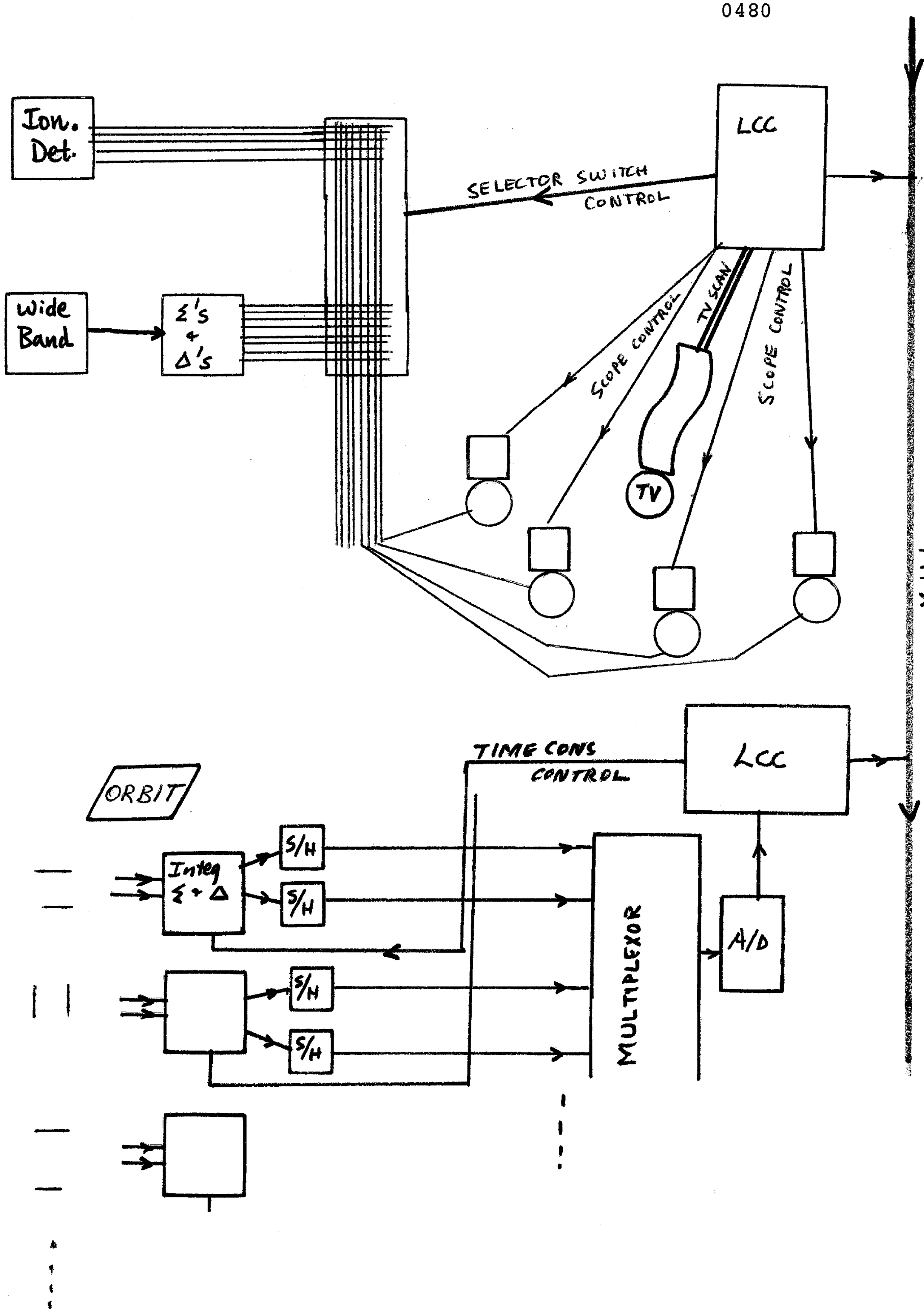

Ion. Det.
Wide Band
Σ's & Δ's
LCC
SELECTOR SWITCH CONTROL
SCOPE CONTROL
TV SCAN
SCOPE CONTROL
TV
MPX
TIME CONS CONTROL
LCC
ORBIT
Integ Σ + Δ
S/H
S/H
S/H
S/H
MULTIPLEXOR
A/D

Fig. 6 and would be triggered by a special high β trigger line around the ring.

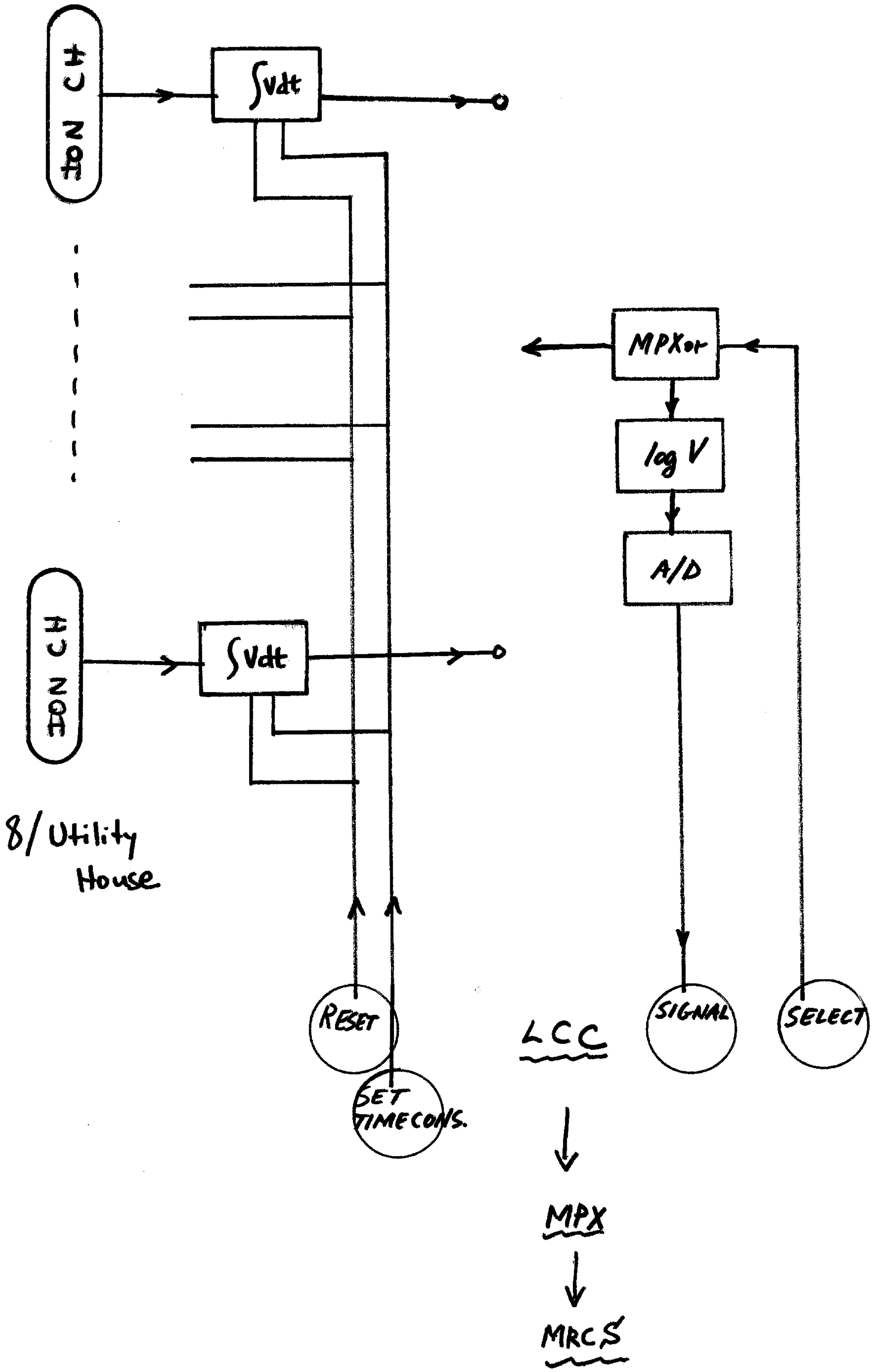
(2) More detailed readout of the beam positions sensors immediately downstream from the injector.

9. <u>Radiation Monitoring</u>

Radiation monitors here do not refer to radiation monitoring for personnel safety. Instead they refer to a set of 200 detectors placed around the ring which can detect beam loss and be used for beam diagnostics. Like the beam position monitors they have the potential for delivering a huge quantity of information. To keep this manageable the scheme shown in Fig. 7 is proposed. Since only $\sim$8 bits are needed the A/D time for 8 channels is $\lesssim$0.1 msec. With 100 msec. time constant beam loss around the ring is observed almost simultaneously. During a 2.6 sec. acceleration and spill this represents 1664 bits/utility house. More flexibility is obtained by making the integrator time constant switchable. The information from the radiation monitors is used for (a) beam diagnostics and (b) to keep a record of integrated beam loss. The former requires switchable gains and integration times whereas this is not desirable for the latter function. Therefore the radiation monitor system could be divided into two distinct subsystems.

Special radiation monitors in a few places (e.g. see Abort & Scraper Systems) can be observed directly without integrator or logarithmic converter. Spikes caused by beam loss in only a few turns might be missed otherwise. The

FIGURE 7


HOT ION CH
∫Vdt
HOT ION CH
∫Vdt
MPXor
log V
A/D
8/ Utility House
RESET
SET TIME CONS.
LCC
SIGNAL
SELECT
MPX
MRCS

information problem is the same as for the wide band beam position monitors and could be solved the same way.

10. Magnet Water Cooling

Water cooling is used for main bending magnets, quadrupoles, main bending power supplies, quadrupole power supplies, and some special magnets.

Float valves in water system tanks in LCW buildings can be monitored by the multiplex transmission system. Make up water can also be monitored. Rather than extend the multiplex system to the LCW buildings, the simplest scheme is to run analog signal cables from each LCW building to the nearest utility building.

In the utility building outlet and inlet pressures as well as flow can be converted to digital signals and sent to the MRCS. This procedure could detect a water leak in the tunnel and cause an immediate shutdown.

11. Service function monitoring

11.1 Tunnel fans

11.2 Smoke alarms

11.3 Fire alarms

11.4 Sump pumps

11.5 Humidity and temperature

11.6 Circuit breakers (in substations)

11.1 - 11.6 represent an interface to DUSAF installed equipment. The number of bits is not large but for some of these functions an alarm signal should trigger an interrupt in the MRCS alerting the operator of the problem.

11.7 Door and safety interlocks are being designed by T. Collins. However, it will probably seem desirable to monitor their status using the multiplex system.

12. Interface to other computers

Under the scheme shown in Fig. 1 communication is with RF, Booster, and Extraction computers. Since 2 of the 3 are already at NAL and are 16-bit Sigma 2's, 16-bit parallel data transmission (in addition to the multiplex channel) is required to and from these computers.

Enable signals between major components are hard-wired signals interconnected in the MRCS. Data transmission to and from the MRCC could be largely in form of display information. In the case of the Booster even this may not be necessary since the Booster control computer is in the same room as the Main-Ring control computer.

The extraction control computer will supply 300 words/pulse of spill information to be used by the MRCC in optimizing the trim quadrupole voltage program.

IV Summary of Information Distribution

Information can be classified as control or monitor. In some cases the distinction is not clear where the control information controls the monitor itself rather than the accelerator, such as setting an integrator time constant in a radiation monitor.

As will be discussed in Section V, the software will be designed to operate in various modes. During an initialization period, the LCC's will be loaded up with programs and control starting values. Taking the upper limit of 25 LCC's x 4096 words each is 102k words which can be transmitted in one second at 100kc word rate. If this data is transmitted in random address rather than sequential (block transfer) mode it adds at most a factor of two in time. From then on only update control information need be sent.

On the other hand, there is no monitor information during initialization, but it starts to flow during the magnet pulsing and other system checkout modes and reaches a maximum during accelerator operation mode.

During accelerator operation information will become available or be needed at various rates and at different places around the ring. The requirements of the 12 systems outlined in Section III are summarized in Table III. Figure 8 is a space-time distribution of this information.

Table III and Fig. 8 obviously represent a very crude first approximation. Nevertheless, certain conclusions can be drawn:

1. The total data flow in the multiplex transmission system during one normal accelerator pulse is 409k bits of 34k 12-bit words; for parallel transmission this is not excessive.

2. The LCC's smooth data flow, or even more, schedule routine data at uncritical times, thus leaving the multiplex lines open to service interrupts when they are most likely to occur.

TABLE III

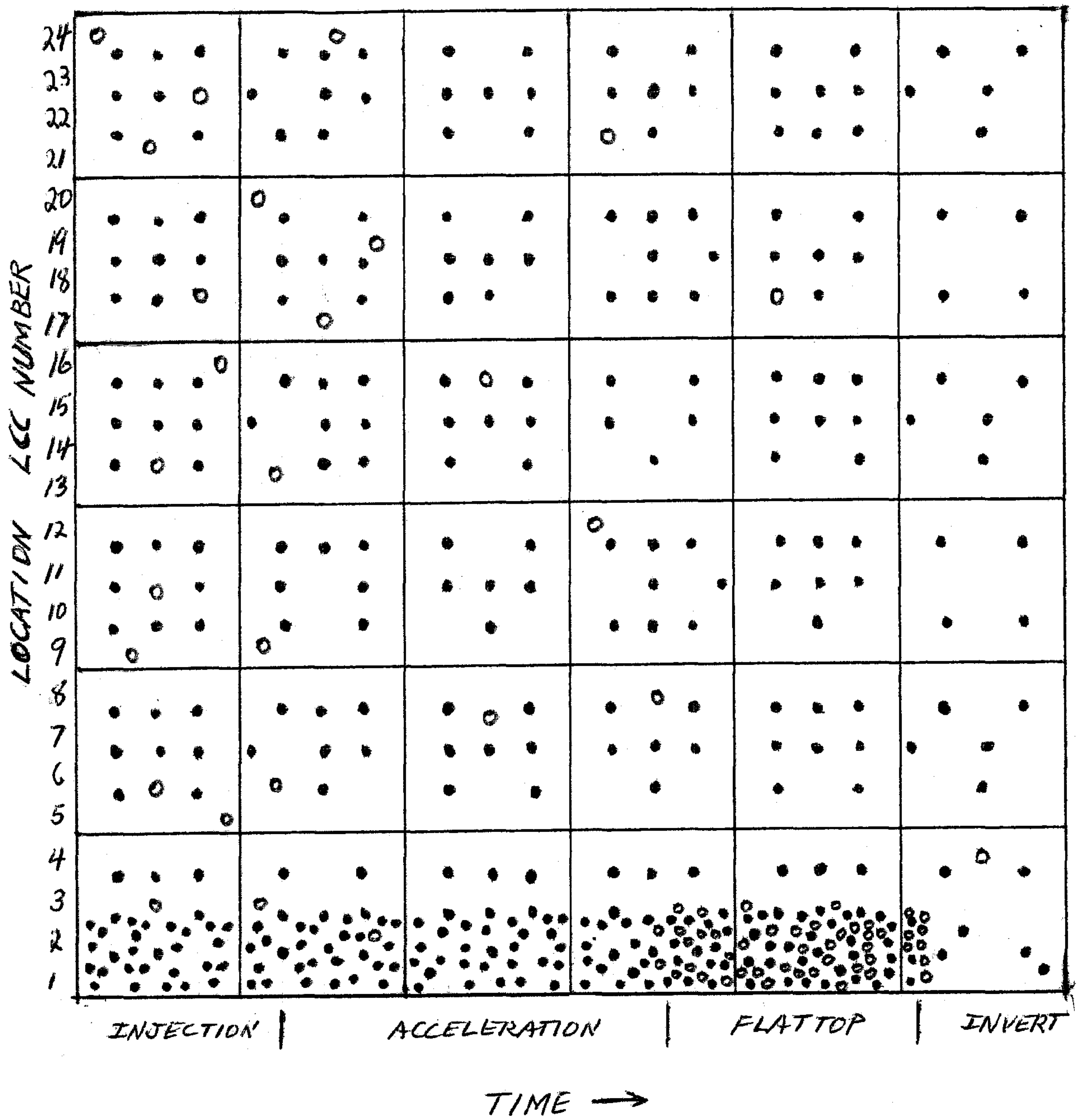
System	Number of Units: Evenly distributed around ring	Number of Units: LCS-1 LCS-2	Number of Units: Abort LCS	Bits / Unit	Monitor bits**: Even distribution in time	Monitor bits**: During or before injection	Monitor bits**: During entire cycle	Monitor bits**: During spill	Control bits**: Even distribution in time	Control bits**: During or before injection	Control bits**: During entire cycle	Control bits**: During spill
1. Main Magnet												
1.1 Bend coarse	22			3028	66,000				616			
Bend fine		2		4400	6,000				2800			
1.2 Quad coarse	11			3028	33,000				308			
Quad fine		1		4400	3,000				1400			
2. Aux Magnets												
2.1 Dipoles	200			2						400		
2.2 Trim Quads												
coarse	22			56						1232		
fine		2		4256						112		8400
2.3 Special trim	16			2						32		
2.4 Sextupoles	24			2						48		
2.5 Spec. Sext.	4			2						8		
2.6 Skew Quad												
AC	5			56						280		
DC		1		4256						56		4200
2.7 Miscell.												
Bump Magnet		(4)		(1000)								(4000)
3. Vacuum												
3.1 Pumps	882			7	5754							
Power supply	24			10	240							
3.2 Gate valves	24			2	48							
4. Abort												
4.1 Mag.triplets			1	(1000)			(500)				(500)	
4.2 Rad Monitors			6	208			1248					
5. Scraper System												
5.1 Mag.triplets	4			(1000)			(2000)				(2000)	
5.2 Rad Monitors	20			208			4160					

TABLE III

System	Number of Units: Evenly distributed around ring	Number of Units: LCS-1 LCS-2	Number of Units: Abort LCS	Bits / Unit	Monitor bits**: Even distribution in time	Monitor bits**: During or before injection	Monitor bits**: During entire cycle	Monitor bits**: During spill	Control bits**: Even distribution in time	Control bits**: During or before injection	Control bits**: During entire cycle	Control bits**: During spill
6. Magnet faults	627			8	5016							
7. Wire survey	2000			7	14000*							
Horiz. tension	240			12	1680*				1200*			
8. Beam positiong												
8.1 Wide band		1		60,000			60,000					
8.2 Ionization		1		60,000			60,000					
Gain controls for 8.1,8.2		2		100						300		
8.3 Closed orbit	200			168			19,200			14,400		
9. Radiation monitors	200			208			41,600					
10. Water cooling												
Pressure, flow	24			112	2688*							
LCW supply	6			14	84*							
11. Service functions	(700)			2	(1400)							
12. Connection to other computers												
12.1 RF Display				12000			12000					
12.2 Booster display				12000		12000						
12.3 Extraction control				3600								3600
display				12000				12000				
TOTAL					138,910	12,000	200,708	12000	6324	16,768	2500	20200
SUBTOTAL						363,618				45,792		
GRAND TOTAL								409,410				

( ) = guess only   * = rate can be lower than 1/pulse
** = time at which information becomes available or is needed

FIGURE 8



SPACE – TIME DISTRIBUTION OF INFORMATION
IN TABLE III

● = 1000 bits monitor
○ = 1000 bits control

3. Only 11% of the data flow is control information. This is a consequence of having LCC's, each of which is loaded up with control information initialization. Then only changes nedd be transmitted during normal pulses. The figures in Table III are averages and do not take into account peaks, e.g. if all 200 dipoles are changed from one pulse to the next instead of only 10% of them. But if only one system is optimized at a time the average figures should be reason-able estimates.

4. Monitor information which is of interest in the MRCS only when an abnormal situation occurs, e.g. interlock chain status, is stored locally and does not appear in the tabulation. When there is a malfunction, an interrupt is triggered causing the MRCC to switch to a different operation mode and request the detailed monitor information. Several different kinds of interrupt will be defined corresponding to degrees of seriousness of the malfunction.

5. Monitor and control information in items 1. - 11. can all travel on the same set of lines clockwise around the ring. Then, all that is needed is one address bus, and one data bus. The function of the links to the RF, Booster, and Extraction control computers has to be defined better before the lines can be specified.

6. The ideal word size for each hardware item varies from 6 to 14 bits. It seems a 12-bit LCC is appropriate; double words would be needed in some cases and in other cases

it might be desirable to do data packing to economize memory.

7. Of the total data flow 39% is associated with displays. It would use as storage a drum, disk, analog tape or memory scope at the device. Therefore the tabulated numbers reduced to memory word use in the LCC's is:

LCC-1,2	∿2000 each
LCC-3,24	∿800 each
LCC-A	∿100 each

The remainder is needed for:

(1) Programs that control data flow, control hardware, scan monitors, generate interrupts.

(2) Monitor information that is not normally sent but is available for fault diagnosis.

(3) Control information sent during initialization.

These numbers indicate that LCC-A may be unnecessary and LCC-1,2 may need 8k memories.

V Outline of Software Systems

Following the scheme proposed for the Booster controls, (ref. L.A. Klaisner "Notes on a Booster Control System", Sept. 12, 1968, TM-40) a series of modes are defined for operation of the control system:

Mode 1 Initialization

Mode 2 Fault Diagnostics

Mode 3 Main Magnets Pulsing

Mode 4 Injected Beam

Mode 5 Accelerated Beam

Switching between these modes would be accomplished by a main executive routine. Switching could occur:

1. By operator action

2. By an interrupt for "serious" trouble which would automatically drop to a lower mode.

Interrupts for "less serious" trouble would inform the operator of the situation, while continuing to run in the same mode. The operator could then make a decision on the action to take.

A general approach to the software is to make it as modular as possible. Standard formats for data storage (bank definitions, sizes, location) would be set up initially, as would definitions for all data transmission and input/output operations. Then, working from flow charts for the total system operation, a large number of rather short and as much as possible general subroutines would be defined, written, debugged, and documented as individual blocks.

These subroutines can be grouped into packages, in order to group together items of a similar nature. Some software writing might proceed along these lines. Parts of one package might use subroutines in another package. The operating modes would draw from more than one package, and share many subroutines in common. The latter feature will be useful in applying overlay techniques for mode switching.

A partial list of subroutine packages might be:

1. Injector (Booster) interface
2. Extraction interface
3. RF interface
4. Accelerator operating conditions
5. Display
6. Beam diagnostics
7. System fault finding and checkouts
8. Trend analysis
9. Maintenance and logging

The next section describes some of these in more detail.

VI Description of Subroutine Packages

1. Injection (booster) interface
2. Extraction interface
3. RF interface

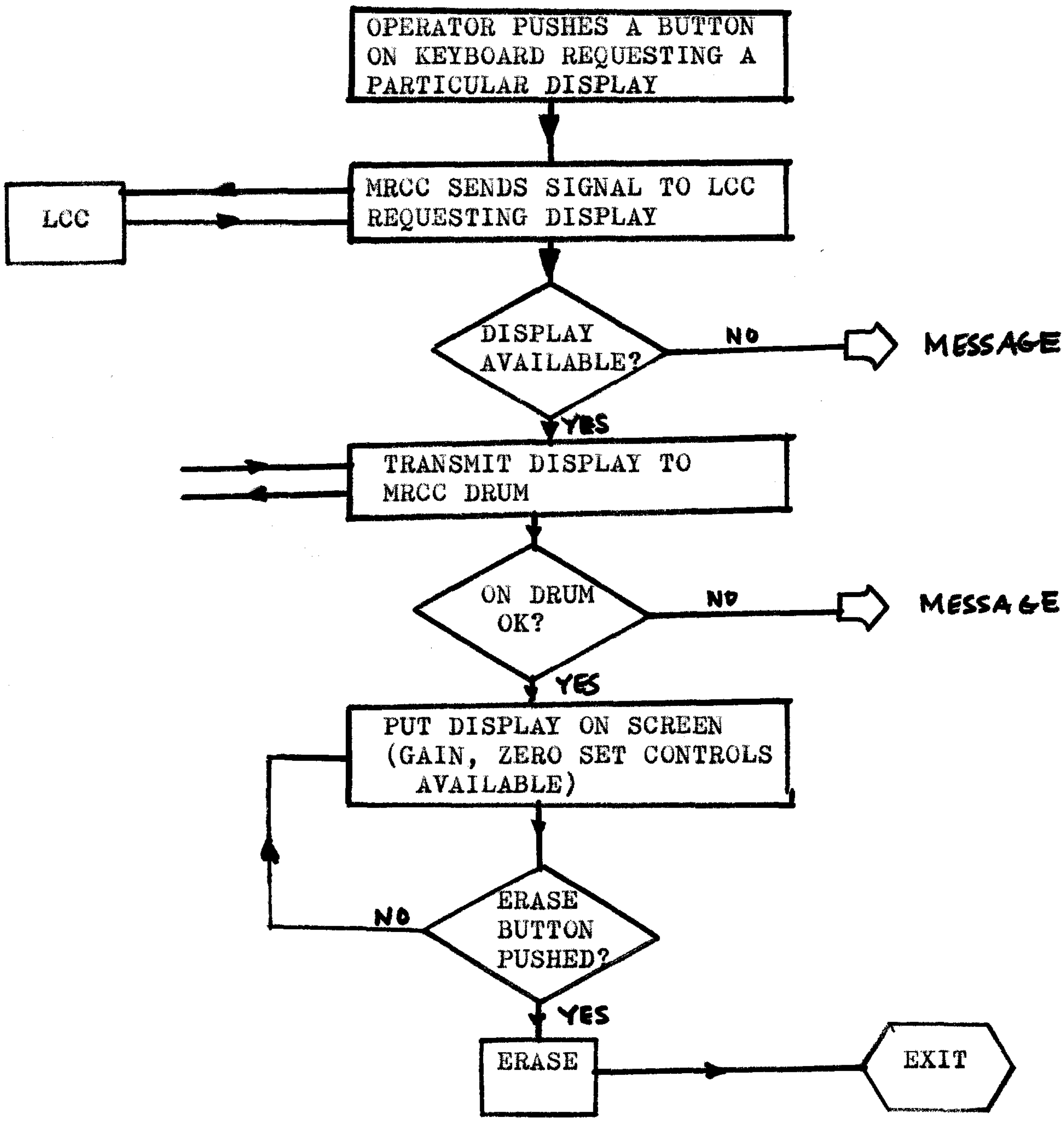
These are still almost undefined. However, one function that will be needed is display transmission. A flow chart of such a subroutine package is shown in Fig. 9. It would also be suitable for sending information from the utility houses to the MRCS.

4. Accelerator operating conditions

4.1 Initialization

Subroutines are needed that can load up a block of memory locations in an LCC (1) locally using a portable I/O device (teletype, card reader), (2) manually from the MRCS using an I/O device (card reader), or a digitswitch or a keyboard, (3) automatically from the MRCS by the operator

FIGURE 9


OPERATOR PUSHES A BUTTON ON KEYBOARD REQUESTING A PARTICULAR DISPLAY
LCC
MRCC SENDS SIGNAL TO LCC REQUESTING DISPLAY
DISPLAY AVAILABLE?
NO
MESSAGE
YES
TRANSMIT DISPLAY TO MRCC DRUM
ON DRUM OK?
NO
MESSAGE
YES
PUT DISPLAY ON SCREEN (GAIN, ZERO SET CONTROLS AVAILABLE)
ERASE BUTTON PUSHED?
NO
YES
ERASE
EXIT

selecting a set of accelerator operation conditions (or a subset for a particular hardware item) that resides on tape or disk.

4.2 Manual optimization "Knob turner"

The "basic" knobs are, of course, binary numbers stored in the LCC's. A "real" knob would be some computed combination of "basic" knobs which might be physically far apart, e.g. two of the power supplies when appropriately powered produce a $\sin 40\ \theta$ skew quadrupole correction, three dipole supplies with the right ratio of levels produce an orbit bump at a given azimuth. Each "real" knob represents a subroutine.

A "physical" knob is one an operator really turns. These should be few in number, and capable of being switched from one "real" knob to another.

The operator should select the knob using a keyboard; an English language description of its function and its current setting appear and remain on a CRT display, along with the new value that is dialed in.

4.3 Saving good operating conditions

A library of sets of operating conditions can be built up on a disk with keyboard functions to add and delete sets. This library forms the basis for future initializations. To record a set requires reading large blocks of numbers from the LCC's via the multiplex transmission system.

4.4 Automatic optimization

This goal has to be reached adiabatically. Some systems, like the main magnet power supplies, will need learning function generators to operate and will from the outset be automatic. Other systems like the dipole correcting magnets could, in principle, be coupled to the closed orbit beam sensors to compute and set the corrections automatically. But it may be preferable not to close this loop until some operating experience is gained.

Of course, if one is close to a maximum in the n-dimensional "real knob" space, one can sequentially servo each knob to the beam intensity and hunt for a maximum. The excursion, though, has to be small enough not to jump to a neighboring maximum.

5. Display

A set of subroutines can be specified for displaying data and messages in different ways on vector and character display CRT's. These subroutines and the knob setter subroutines can be built into a checkout and operation program by a person building a particular system. In order to make this possible it is essential that each subroutine be thoroughly checked out and well documented.

Many interesting and useful displays will aid in accelerator operation. Each will require a subroutine package but many subroutines will be in common. Some displays are vacuum around the ring, emittance of injected beam, variation of ν_x, ν_y with momentum.

Permanent records of some displays, such as items produced under (6) below, should be obtainable photographically or using a plotter. Light pen operator feedback to the display would be one aspect of this.

6. Beam diagnostics

There is a general class of operations where some parameter(s) is purposely varied and the effect on beam sensing electrodes observed. This variation, say of inflector voltage, B injection, orbit bump magnitude, can be done in a systematic way going from a start value, V_s, to an end value, V_e, in steps of Δ where V_s, V_e, Δ are set by the operator. The dependent variable (beam position) can then be displayed as a function of the independent variable.

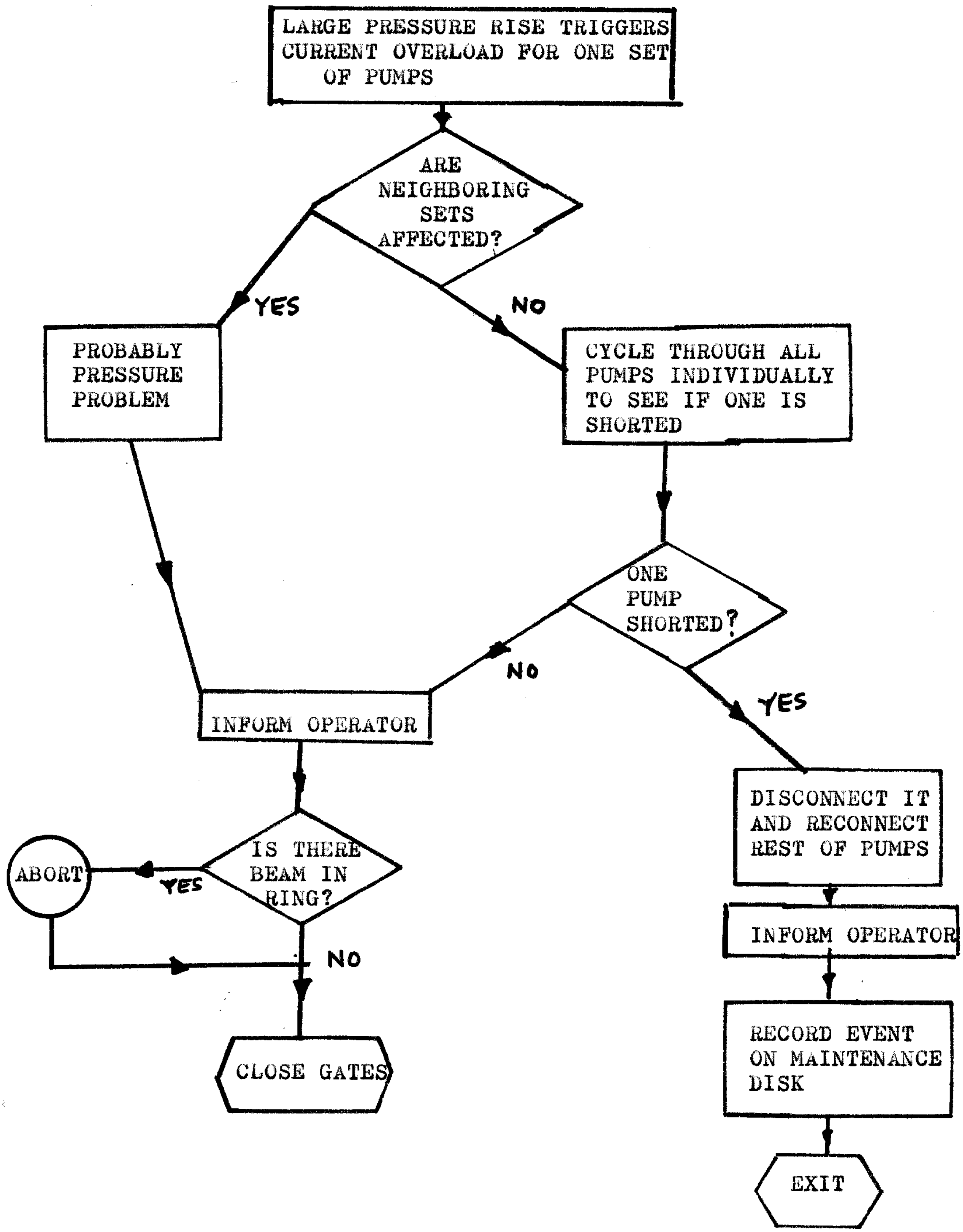
7. System fault finding and check out

At the time a fault occurs an interrupt triggers the MRCC and it drops into a fault mode. The status of the systems at the time the fault occurred is preserved in the LCC memories and can be read into the MRCS and displayed.

The operator can then initiate diagnostics on the troublesome component. Many of these diagnostic routines will be developed during installation of equipment in the ring and later incorporated as blocks in the overall software system. Many of these diagnostic programs will operate out of the LCC's.

An example of a program for the control of a pair of fast acting gate valves is shown in Fig. 10.

FIGURE 10


LARGE PRESSURE RISE TRIGGERS CURRENT OVERLOAD FOR ONE SET OF PUMPS
ARE NEIGHBORING SETS AFFECTED?
YES
NO
PROBABLY PRESSURE PROBLEM
CYCLE THROUGH ALL PUMPS INDIVIDUALLY TO SEE IF ONE IS SHORTED
ONE PUMP SHORTED?
NO
YES
INFORM OPERATOR
DISCONNECT IT AND RECONNECT REST OF PUMPS
IS THERE BEAM IN RING?
ABORT
YES
NO
INFORM OPERATOR
CLOSE GATES
RECORD EVENT ON MAINTENANCE DISK
EXIT

8. Trend analysis

There are many functions such as vacuum, wire survey, unbalance current in magnets which should be recorded on a long term basis. By looking at the trend over a given time potential trouble can be spotted. A rise in pressure or an increase in unbalance current over the previous 20 accelerator pulses might forwarn of a bad pump of magnet trouble. A steady statistically significant change in magnetic position over several days might mean a portionoof the tunnel is settling or might mean a wire pickup wasn't working right.

All of these operations can be done with the same program. Only four parameters need be set:

(1) location of the variable

(2) how often should it be sampled

(3) how many values should be kept

(4) what level of slope should warn the operator

Even though the points can be stored on disk, this program represents a sizeable computing load because of the large number of variables to check.

9. Maintenance and logging

A natural function for a computer is to keep a log. Any of the trends mentioned above could be printed out as part of a daily log.

Information such as integrated radiation dose on radiation monitors, amount of time each item operates, can be tabulated and stored on disk on a daily, weekly, and monthly basis with printed copies when desired. If the disk if a removable pack (or if magnetic tape is used) then a backup can be provided so not more than one week's records are lost in case the information is erased.

Maintenance records can also be kept by the computer. Punched cards can be produced by the computer telling which pump needs replacing and which water pump bearing needs oiling this week. Reading the cards back in could tell the computer the assigned task is completed.

Another useful function would be periodic exercising of infrequently used components such as gate valves.

Finally, since a computer will be available it ought to be used for computerized wiring lists.

VII Specification of Computers and Hardware

This is very preliminary and should be considered more as a check list than anything definitive.

1. LCC Hardware

1.1	Word size	12-bit
1.2	Memory size	8k in LCC-1,2
		4k in LCC-3 - 24
1.3	Cycle time	$\lesssim$1.5 μsec.
1.4	Index registers	$\gtrsim$1

1.5 I/O devices. None normally except for 1-2 portable modules consisting of a line printer, card reader/punch combination.

1.6	Interrupt	$\gtrsim$2

2. <u>MRCC Hardware (configuration in Figure 11)</u>

2.1 Word size 16-18 bit

2.2 Memory size $\gtrsim$16k (see discussion under software)

2.3 Cycle time $\sim$1.0 μsec.

2.4 Index registers $\gtrsim$3

2.5 Accumulators $\gtrsim$2 (however, a total of $\gtrsim$8 general purpose registers is very useful)

2.6 Hardware multiply-divide

2.7 I/O Devices

(a) 1 disk with removable pack for logs and maintenance records (500k words)

(b) 1 disk with removable pack for program and temporary data storage (500k words)

(c) 1 line printer $\gtrsim$600 ℓ/m

(d) 1 card reader $\gtrsim$600 c/m

(e) 1 card punch $\gtrsim$800 c/m

(f) 1 fast drum for flicker free scope displays $\sim 10^6$ bits $\gtrsim$200kc bit transfer rate

(g) 2 display consoles with keyboards (in control room)

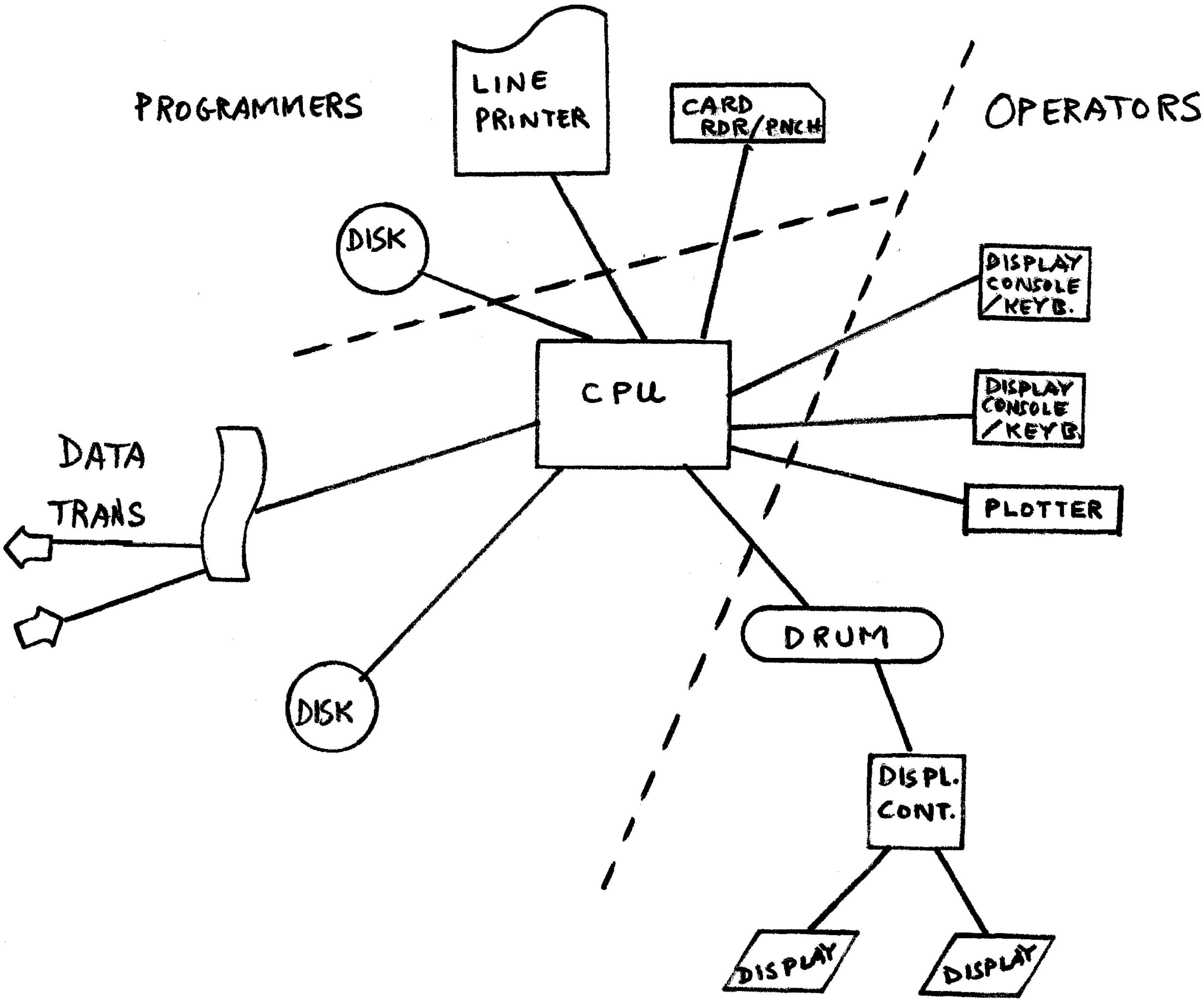
(h) 2 large vector display scopes. Color TV seems to be a good technique to investigate.

(i) plotter

2.8 Interrupts $\gtrsim$8

2.9 Memory protect desirable

FIGURE 11


PROGRAMMERS
LINE PRINTER
CARD RDR/PNCH
OPERATORS
DISK
DISPLAY CONSOLE /KEYB.
CPU
DISPLAY CONSOLE /KEYB.
DATA TRANS
PLOTTER
DRUM
DISK
DISPL. CONT.
DISPLAY
DISPLAY

2.10 Expansion: to 32k all directly addressable (expansion capability for eventual evolution into a central computer)

3. Computer software

3.1 Languages: Relocatable assembly language with reasonable pseudo-ops on both computers; Fortran for MRCC.

Fortran and assembly language should be easily linked, with transmission of information between subroutines via argument lists possible. Rapid transfer in and out of subroutines is important (since overall software philosophy is to make it very modular).

3.2 Other languages

An elegant approach would be to write a new compiler with a control language (suggested by Maschke). Unless such a compiler is developed elsewhere, the programming time is too long for NAL to write it and keep on schedule. Many people with limited programming experience will be writing programs as part of their development of a hardware system and Fortran is more universally known. An approximation to a control language is to build up a large collection of general purpose subroutines and functions that perform control operations.

3.3 Loading and Communication

Software is needed to allow loading LCC programs via multiplex transmission system. Software allowing dialog between computers is also needed.

3.4 Time sharing

A certain amount of time sharing ability is needed to rapidly swap pieces of program in and out of core. The broader question of debugging programs while the accelerator is operating needs to be examined but is hard to answer at this time. To do both jobs on one computer requires a sophisticated time sharing monitor with memory protect features, probably extra money, and an extra console. An alternative is to have another MRCC for programming without all the peripherals and less memory. This has the advantage of providing a (partial) spare computer in case of fire in the MRCS, but complete check out of a new program cannot be done with it. The two computer approach is more expensive but this is somewhat offset by increased programming cost on the single time sharing system.

4. Hardware

The multiplex system would require a 12 line address bus, a 12 line data bus; other lines around the ring are a 4 line interrupt bus, timing bus and enable bus (includes abort). Parity lines are necessary in each bus. Whenever possible multiplex switches, A/D and D/A equipment, sample and holds should be commercially available building blocks.

VIII Summary

Arguments in favor of local storage were presented in Section IV based on information flow during an accelerator pulse. An additional argument is based on the interrupt situation, e.g. the pumps in 1/24 of the ring go off and trigger an interrupt during transmission of the magnet power supply voltage program. If the transmission is only of small variations from the already locally stored program, no great harm is done, but if there is no local storage then power supply control would suddenly be removed.

A further argument in favor of local storage might be purely economic. It costs approximately the same to buy a 4k 12-bit computer as to add an extra 4k of memory to a 16-bit computer.

This study has left many questions unanswered but hopefully has served to organize the problem so it can be attacked piece by piece, priorities of the various pieces can be established and available manpower used efficiently.

The basic multiplex scheme and enumeration of control functions is developed from previous work on the Main-Ring control system (ref. R. Littauer, "Information Transmission by Time-Programmed Multiplexing", August 30, 1967, FN-51) and L.C.L. Yuan, R. Littauer, K.B. Mallory, M.W. Sands, Chapter 11 in NAL Design Report, July, 1968) although the analog transmission of data is replaced by digital because of an anticipated noise problem. Discussions with R. Cassel and F. Shoemaker have been essential in defining the hardware systems described in Section III.